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## Abstract

Experimental tests were conducted to examine the behavior of naturally occurring turbulent spots over a wide range of gas-turbine representative conditions including: subsonic and supersonic flow, acceleration parameters, and freestream turbulence intensities. Turbulent spot propagation velocities, spreading angles, generation rates, and overhang profiles were determined using high-frequency data acquisition equipment in combination with high-density thin-film technology and hot wire anemometry. A new theory for the influence of the turbulent spot disturbance on a laminar boundary layer has been developed and supported with experimental and computational data. Modelling of the transition zone intermittency using spot characteristics was conducted using a new Dynamic Spot Model.

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# Final Technical Report

**United States Air Force Office of Scientific Research**
**Grant Number F49620-92-J-0079**

for period 15 December 1991 - 31 August 1995

## Turbulent Spot Generation and Growth Rates in a Compressible Boundary Layer

Submitted by

Professor T.V. Jones - Oxford University, UK
Professor J.E. LaGraff - Syracuse University, USA

October 1995

# Turbulent Spot Generation and Growth Rates in a Compressible Boundary Layer

## Project Summary


### Abstract

Experimental tests were conducted to examine the behavior of naturally occurring turbulent spots over a wide range of gas-turbine representative conditions including: subsonic and supersonic flow, acceleration parameters, and freestream turbulence intensities. Turbulent spot propagation velocities, spreading angles, generation rates, and overhang profiles were determined using high-frequency data acquisition equipment in combination with high-density thin-film technology and hot wire anemometry. A new theory for the influence of the turbulent spot disturbance on a laminar boundary layer has been developed and supported with experimental and computational data. Modelling of the transition zone intermittency using spot characteristics was conducted using a new Dynamic Spot Model.


### Experimental Approach

Two facilities were employed, one producing compressible flow and the other incompressible. The Oxford University 6" ILPT (Isentropic Light Piston Tunnel), which is a short-duration transient subsonic/supersonic facility, was used to test a range of Mach numbers from 0.55 to 1.86 and a range of pressure gradients from adverse to strong-favorable. The Plexiglass test plates were covered by a sheet of Kapton™ and coated with thin-film gauges. The thin-film transient heat transfer technique has been developed and well documented over several decades at Oxford University and is the central technology, in its present form, of the present experiments that enables the detection and tracking of turbulent spots. In addition to thin-film heat transfer gauges a variety of instrumentation types could be used in the test-section including: total/static pressure probes and/or a hot-wire boundary layer probe which made possible the measurement of free-stream turbulence and spot characteristics above the surface. Very fast response thin film instrumentation was specifically developed for the program. This unique, miniature thin-film technology enabled the unobtrusive detection of naturally occurring turbulent spots throughout the entire transition region. Thin-film heat transfer gauge sizes have been miniaturized to 0.1mm x 1.0 mm. These minute gauges can be packed to a maximum density of 13 gauges/cm$^2$, inclusive of leads to/from the gauges. The high frequency electronics enabled instantaneous surface heat transfer data to be gathered over a wide range of Mach numbers, flow acceleration parameters, and freestream turbulence intensities. Turbulent spot characteristics were inferred from their detection by time-resolved heat transfer traces which located the boundary between the laminar boundary layer and the turbulent spot where heat transfer rates increased by an order of magnitude. Leading and trailing edge turbulent spot velocities were measured as a fraction of the freestream velocity. Turbulent spot lateral spreading and the behaviour of the becalmed region

were also characterised as a function of these flow conditions.

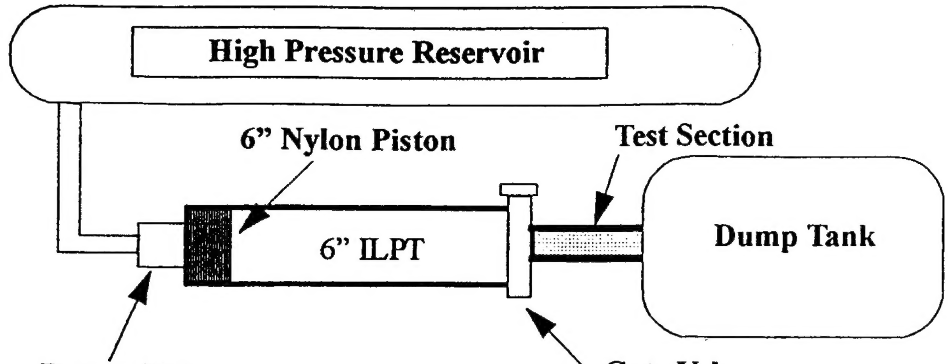
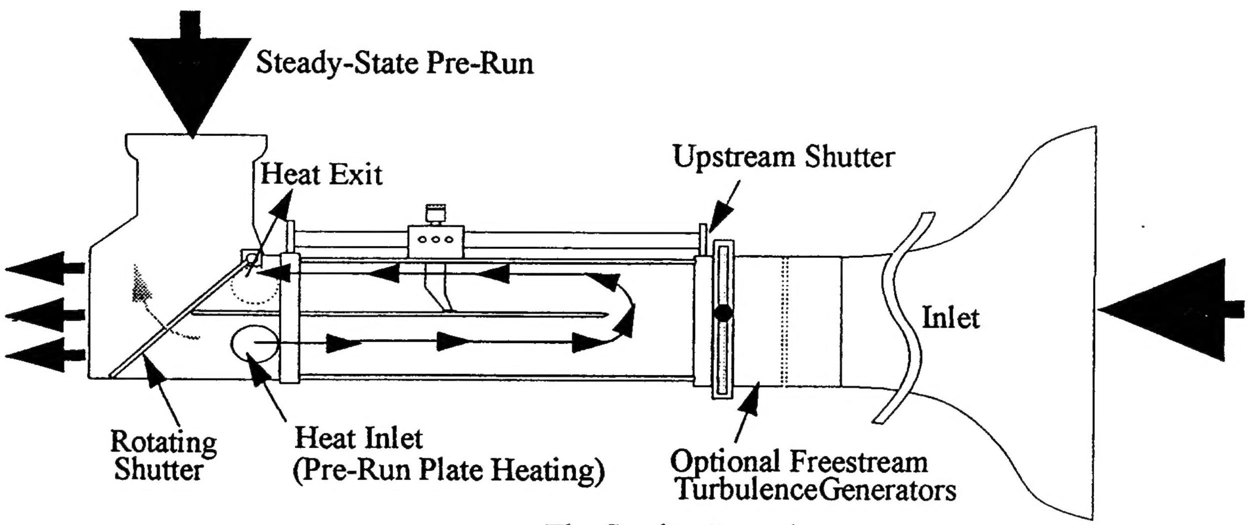



Figure 1

The 6"x8", four-fan tunnel is capable of maintaining freestream velocities ranging from 30 m/s to 145 m/s with variable freestream turbulence from 0.2%-20% over a test-plate measuring 6"x12"x1/2". The tunnel is capable of operating in either a steady state or transient mode, the latter accomplished by combining a heater and a fast-response trigger system which 'switches' on the flow through the test-section. The flap (located to the rear of the test-plate), when held in 'ready' position, causes the tunnel to draw air from ambient through an auxiliary inlet, resulting in a no-flow condition in the test-section. Once the fans are up to speed and drawing air through the auxiliary inlet, the trigger is released and the flap shuts resulting in an 'immediate' mass-flow through the test-section which provides the transient nature of the facility, see schematic. This




The Suction Tunnel

mode of operation allowed thin-film transient heat transfer techniques to be employed in an otherwise steady flow tunnel.

Selection of this tunnel was based on its larger span-wise working section which is required for the determination of generation rate. Between the converging portion of the tunnel and the test section are several removable sections which are used to add free stream turbulence to

the flow via turbulence generation grids. The test section is equipped with a hot-wire traverse mechanism which was recently modified to permit all X, Y, and Z translations for hot-wire and surface-mounted thin film comparisons.

## Results

Detailed turbulent spot property results have been reported in the publications listed at the end of this report and will be also included in the D. Phil thesis of Hofeldt to be published. Sample results are listed in the table at the end of this report.

## Theoretical Support and Modelling

A new theory governing the behaviour of the becalmed region was developed. The results of the theory were computed using unsteady, viscous CFD and agreed with the experimental measurements.

The quantification of the geometric parameters of the growing spot has enabled the development of a computer program which calculates the trajectories of all important turbulent spot characteristics. This software produces the time dependent generation and propagation of the turbulent spots such that the intermittency through the transition region may be evaluated. This is called the Dynamic Spot Model. The resultant output can be easily patched into existing CFD codes to connect the laminar and turbulent portions for accurate heat transfer prediction, for example.

## Transition to Applications and Industrial Relevance

The location and extent of the region where a laminar boundary layer undergoes transition to a turbulent boundary layer is very important in gas turbine design. This is true for both the turbine and in the compressor section where the state of the boundary layer under the influence of passing wakes is vital to loss prediction and the mechanism of separation. In addition, the heat loads to turbine blading and hence the low cycle fatigue failure is highly dependent on the nature of the boundary layer transition. The modelling of this transitional region in CFD design codes has been highly dependent on empirical correlations for intermittency data from controlled experiments. The potential for improving the prediction of intermittency by using a turbulent spot dynamic model is now a realistic possibility. This approach is highly dependent on a detailed knowledge of the physical characteristics of spots themselves especially under the influence of varying flow parameters representative of modern gas turbine engines. These characteristics have been determined in the experiments undertaken in the present grant. A spot dynamic model has been developed based on these measurements.

Film cooling is used extensively in the HP turbine of all gas turbines. The presence of film cooling usually causes the boundary layer and film to be turbulent and this is general increases losses in the stage. There is therefore a move to cool by other means, especially on the suction surface of the airfoil, and transition therefore again becomes an issue. The increased used of thermal barrier coatings in conjunction with improved internal cooling in this context in new engines is also important. In LP turbines film cooling is seldom used as heat transfer levels are lower. However, the question of heat transfer is still an important design issue. In addition, the control of separation is dominated by the state of the boundary layer. In the case of the compressor, transition is very important design parameter for controlled diffusion blades as discussed by Cumpsty in the cited reference.

The present research represented by this report has now fully characterized the physics of naturally occurring turbulent spot gross characteristics. This data has been reported in the literature and some has been included in this report and in the D. Phil. (Ph.D.) thesis of Hofeldt. Also reported is the development of a practical time-marching code based on spot characteristics for the prediction of intermittency distribution in boundary layer flows.

Examples of specific technology transitions of the results of this AFOSR supported research to a non-research activity are included in two recent publications where the authors make us of the principles established here. These references are listed at the end of the Publications section of this report. Cumpsty describes the importance of understanding the "becalmed" region behind patches of wake turbulence in a laminar boundary layer. Simon acknowledges the practical importance of intermittency models based on turbulent spot characteristics for gas turbine heat transfer prediction now that the spot data exists (from the AFOSR research reported herein). Extensive discussions with Rolls-Royce staff have also taken place in Oxford showing the potential of the spot intermittency models in heat transfer codes.

Other transition-to-application activities include the 1993 Minnowbrook Workshop of End-Stage Boundary Layer Transition hosted by the Principle Investigators of this grant. Turbine engine manufacturers participated and the summary of the report of the conference prepared by R. Narasimha specifically highlighted the importance for design of the new spot data emerging from the AFOSR-supported research in this grant.

## Publications


Clark, J.P., 1993, '*A Study of Turbulent-Spot Propagation in Turbine-Representative Flows'*, D. Phil Thesis, Oxford University, Oxford, U.K. (available through *University Microfilms*, Ann Arbor, MI).

Clark, J.P., Jones, T.V., and LaGraff, J.E., 1994, 'On the Propagation of Naturally-Occurring Turbulent Spots', *Journal of Engineering Mathematics, Vol. 28, pp. 1-19.*

Clark, J.P., Magari, P.J., and Jones, T.V., 1993, 'On the Distribution of the Heat-Transfer Coefficient in Turbulent and "Transitional" Wedges', *International Journal of Heat and Fluid Flow*, Vol. 14, No. 3, pp. 217-222.

Clark, J.P., Magari, P.J., Jones, T.V., and LaGraff, J.E., 1993, 'Experimental Studies of Turbulent-Spot Parameters Using Thin-Film Heat-Transfer Gauges', NATO/AGARD CP-527, pp. 7.1-7.14.

Clark, J.P., LaGraff, J.E., Magari, J.P., and Jones, T.V., 1992, 'Measurement of Turbulent Spots and Intermittency Modelling at Gas-Turbine Conditions', NATO/AGARD CP-527, pp 7.1-7.14.

Clark, J.P., Jones, T.V., Ashworth, D.A., and LaGraff, J.E., 1991, 'Turbulent-Spot Development in a Mach 0.55 Flow', *Proceedings of the Royal Aeronautical Society Boundary Layer Transition and Control Conference,* Cambridge, U.K., Vol. 1, pp. 21.1-21.9.

Hofeldt, A.J., 1996, '*Thin-Film Development and the Investigation of Naturally Occurring Turbulent Spots*', D. Phil Thesis, Oxford University, Oxford, U.K.

LaGraff, J.E., (Editor), 1993, Syracuse University Minnowbrook Workshop on End-Stage Boundary Layer Transition. (Proceedings).

## Transition to Applications References

Simon, F.F., 1994 'The Use of Transition Region Characteristics to Improve the Numerical Simulation of Heat Transfer in Bypass Transitional Flows', NASA TM 106445, Presented at The Fifth International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, Hawaii,.

Cumpsty, N.A., Dong, Y., Li, Y.S., 1995, 'Compressor Blade Boundary Layers in the presence of Wakes', ASME 95-GT-443 presented at The International Gas Turbine and Aeroengine Congress on Exposition, Texas, USA.

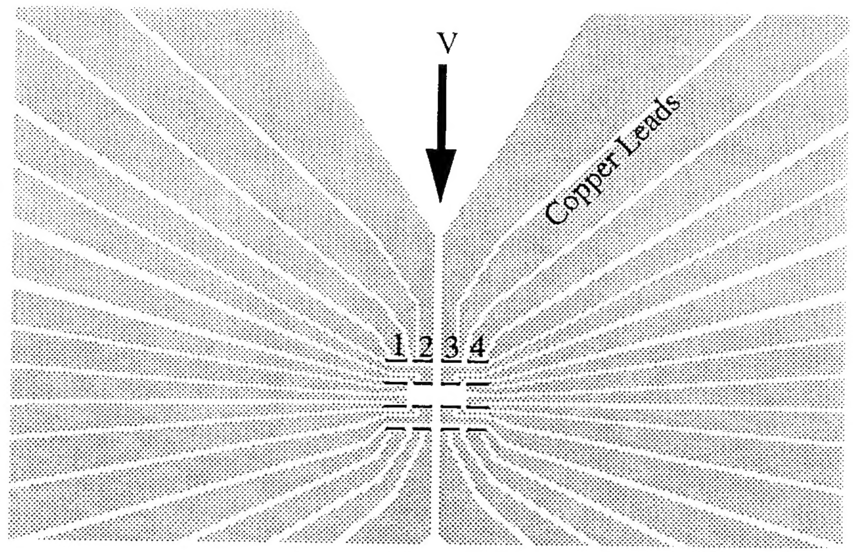



**Figure 1** This pattern is used to obtain the generation rate of turbulent spots. A total of 16 Platinum gauges in 1.25 $cm^2$ were essential in order to determine the generation rate.

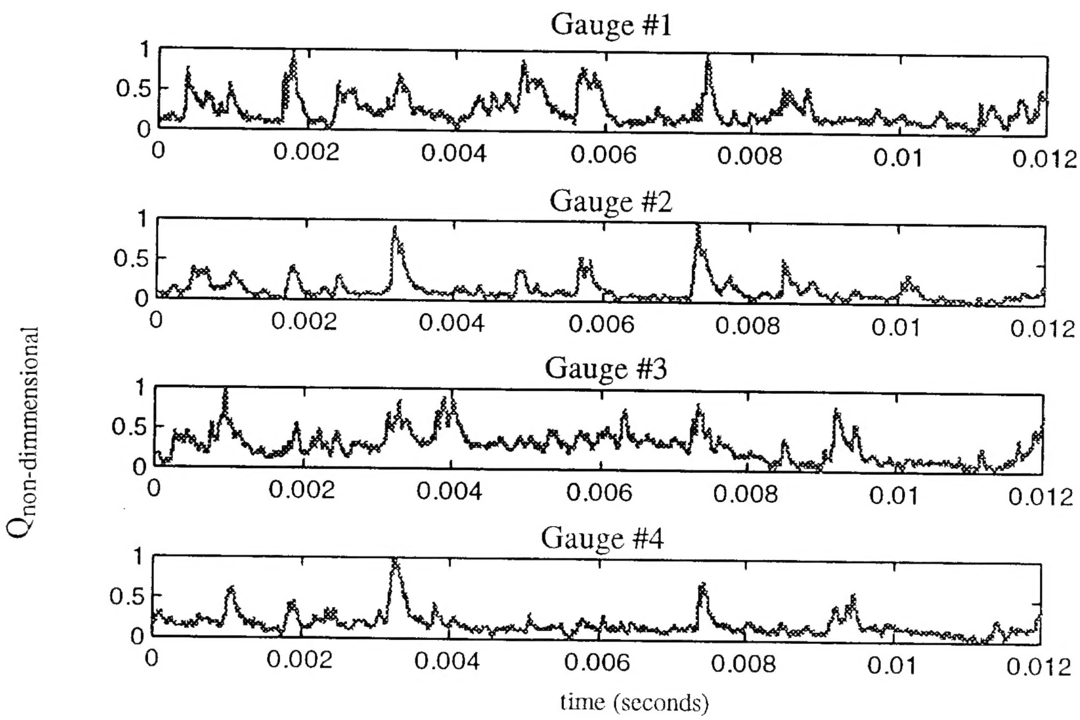



**Figure 2.** The traces shown correspond to the first row of heat transfer gauges in figure 1. This data, when combined with data from the remaining 12 gauges, has been analyzed to extract the turbulent spot generation rate. The generation rate and other parameters can then be incorporated into a numerical model to generate spot loca-

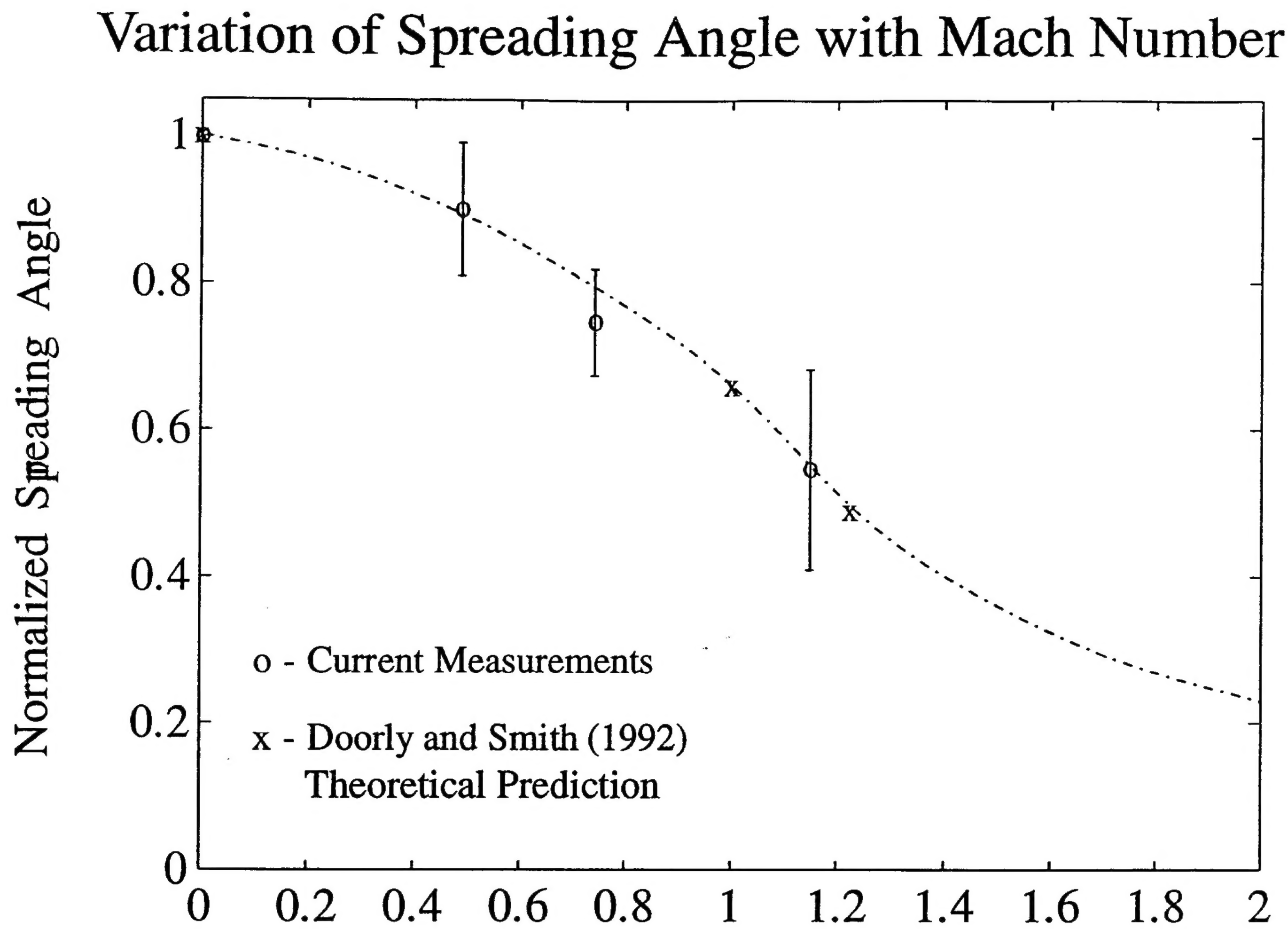
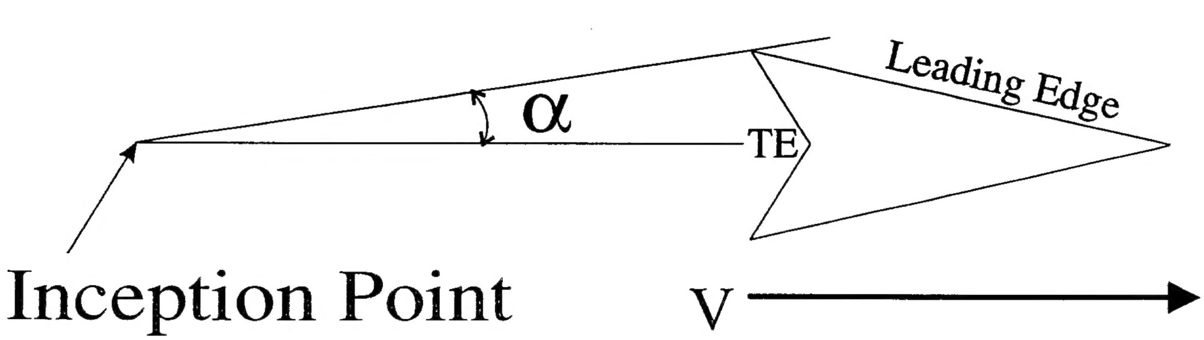



**Figure 3.** (Mach Number)^0.5

$$\text{Normalized Spreading Angle} = \alpha/\alpha_{M=0}$$



## Behavior of Spot Celerities with Favorable Pressure Gradient

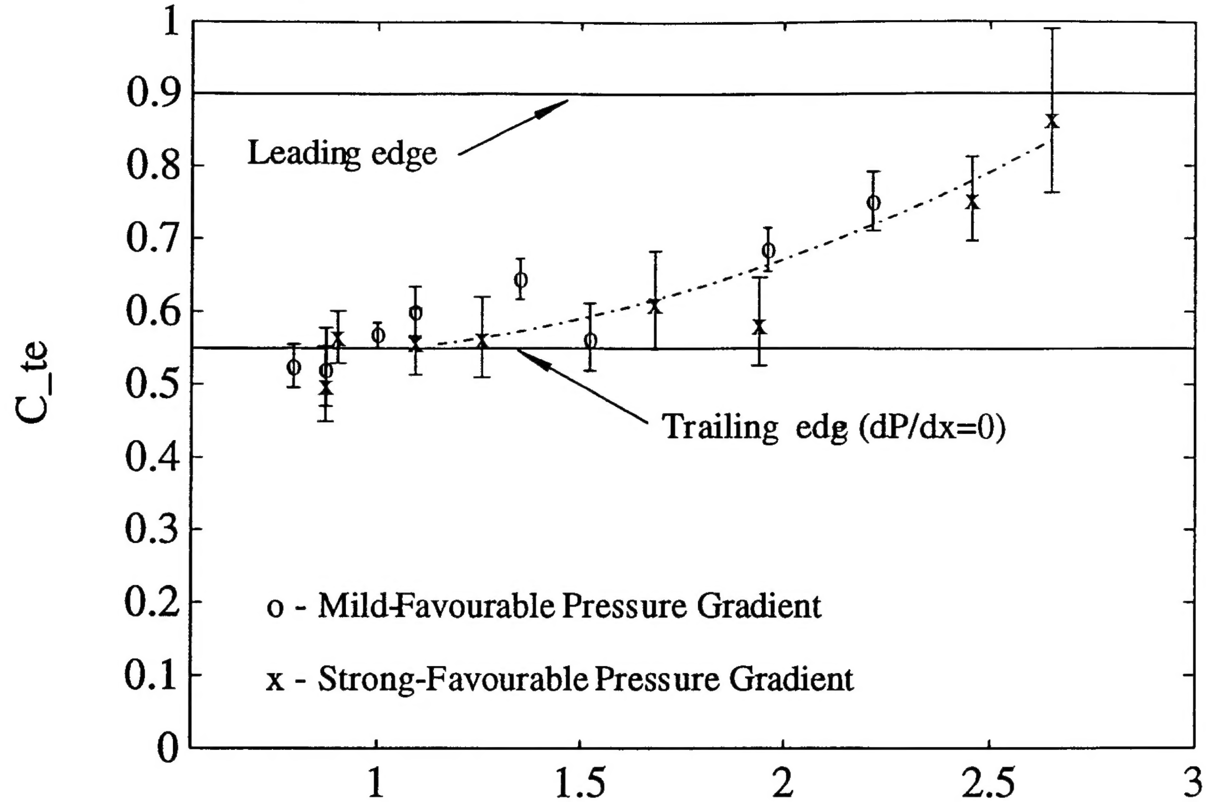
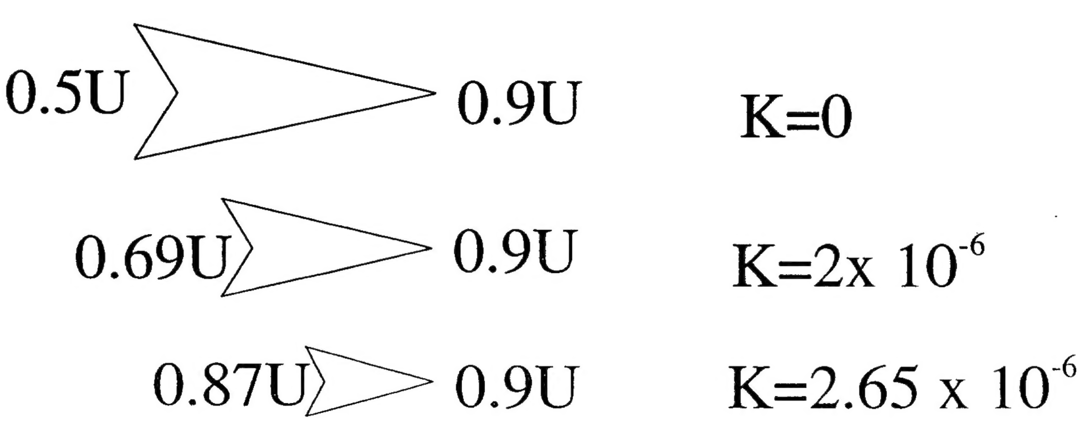



**Figure 4.** Acceleration Parameter, K (x1.0E+06)
$K=(\nu/U^2)*(dU/dx)$
$C_{te}$=Trailing Edge Fractional Propagation Rate

An increase in the accerlation parameter results in an increase of the trailing edge spot velocity. This greatly inhibits the growth of the spot because the trailing edge travels at approximately the leading edge value as acceleration parameter approaches $2.5x10^{-6}$.



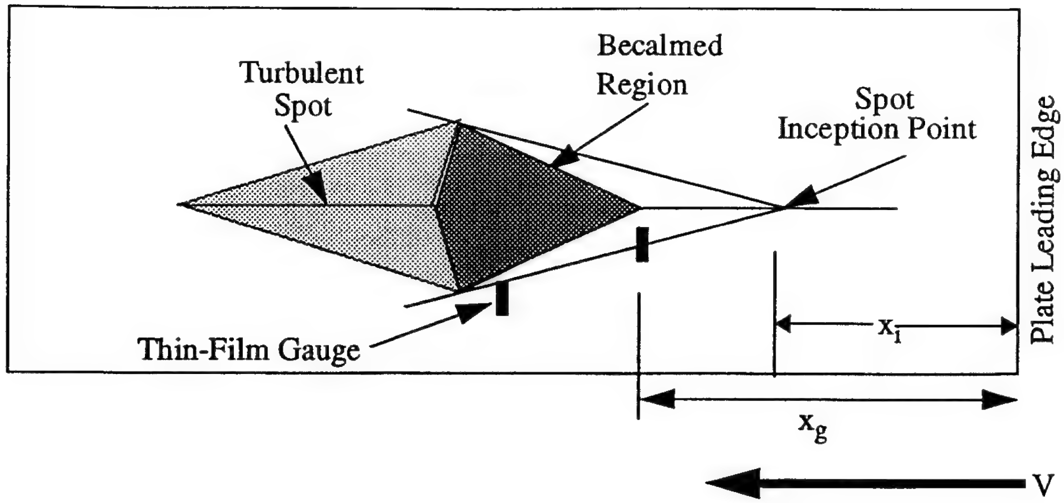



**Figure 5.** Planview of Turbulent Spot and Becalmed Region
The turbulent spot originates at the inception point, $x_i$, after which time it develops into a mass of fluid which grows as it moves along the surface. The forward portion of the spot typically travels at 90% of the freestream while the trailing edge typically travels at 50%, resulting in turbulent spot growth. The becalmed region typically trails at 30% of the freestream velocity.

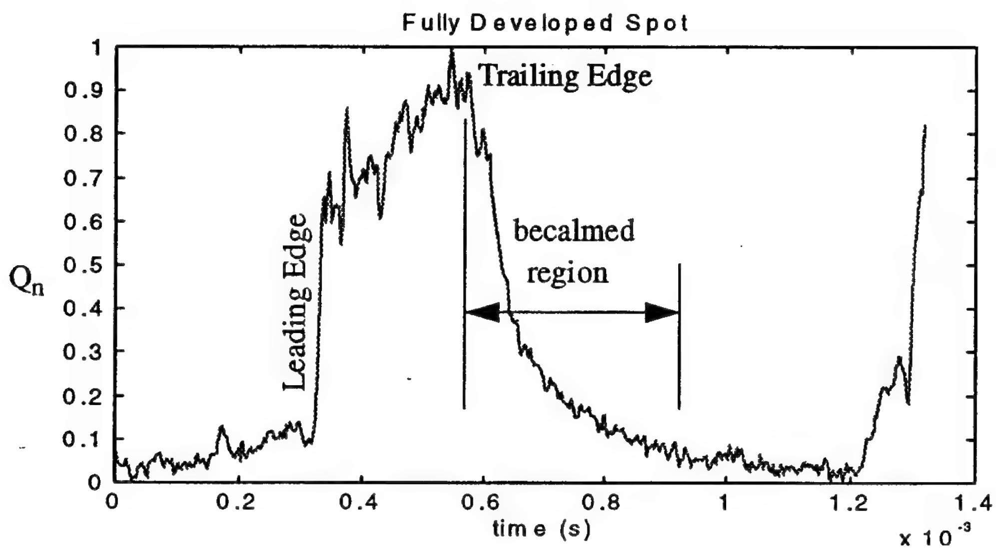



**Figure 6.** Surface heat transfer variation in the turbulent spot becalmed region. The maximum heat transfer within the spot is equivalent to that of a fully turbulent boundary layer.

Typically the becalmed region has been excluded from previous works in calculating the surface heat transfer increase from turbulent spots.

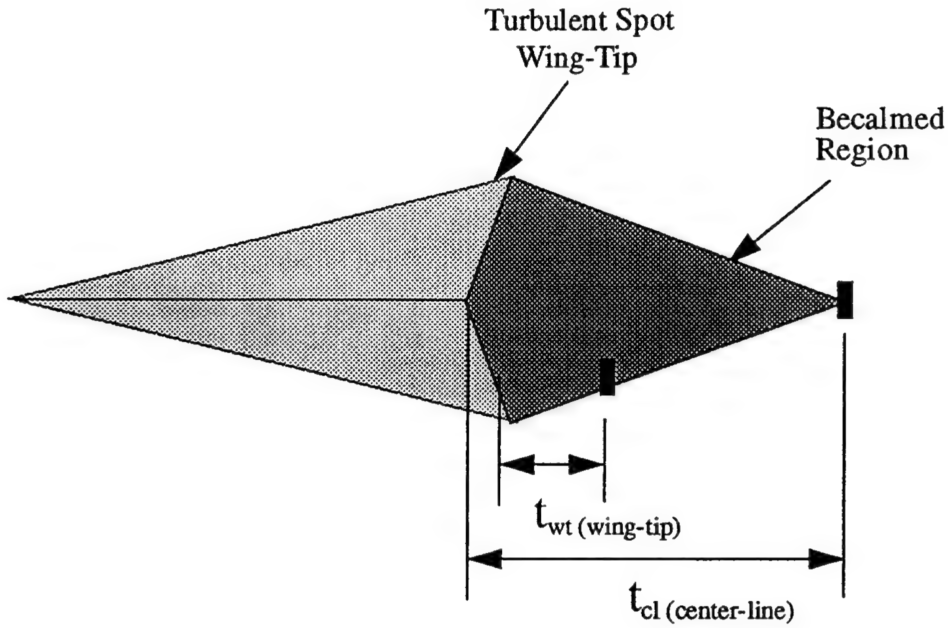



**Figure 6.** The spanwise variation of the becalmed region as shown by centerline and wingtip heat transfer gauges, corresponding to t/T values where $t_{cl}/T=1$ and $t_{wt}/T<1$, respectively. See the following figure for corresponding sample data.

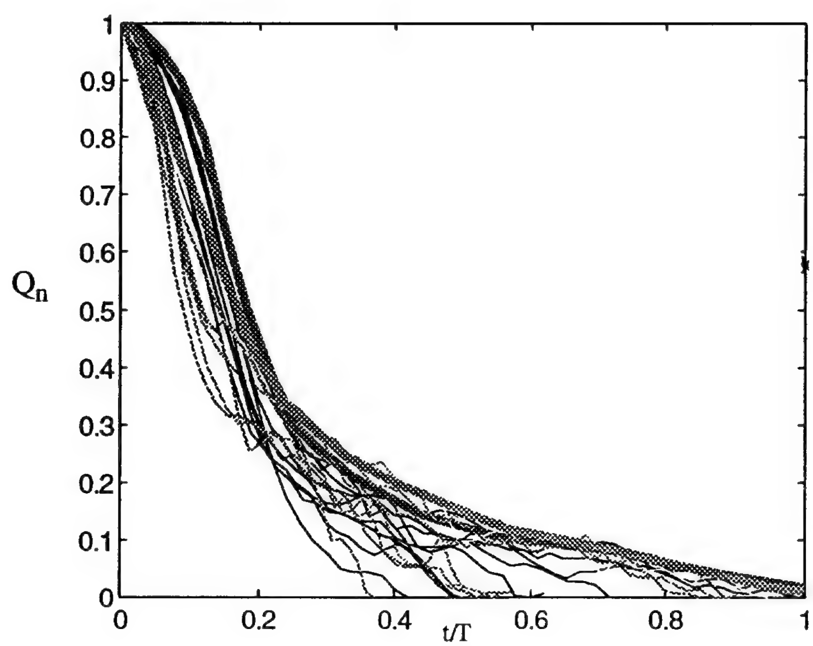



**Figure 7.** Becalmed region heat transfer profiles inclusive of wingtip traces (t/T < 1), to show spanwise variation.

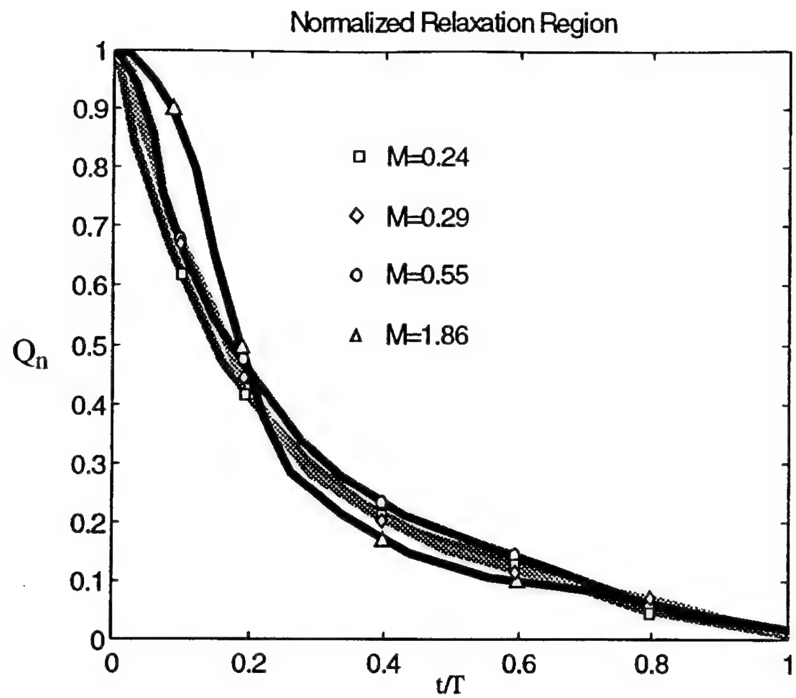



**Figure 8.** Becalmed region heat transfer profiles for all centerline measurements. The convex portion of the M=1.86 flow is an effect from the high Mach number flow. This convex portion of the curve would move toward a concave shape with increasing sample frequency.

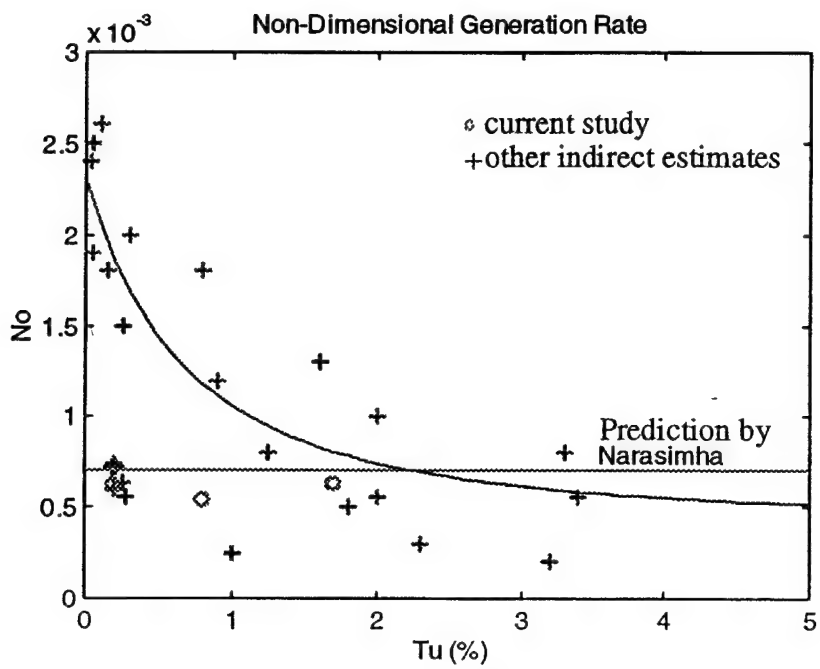



**Figure 9.** The Non-dimensional generation rates ($N_0$), obtained in the current study show a more constant trend than other studies. The current study is the only study which has *directly* measured the generation rate, all others are calculated based on a measured transition

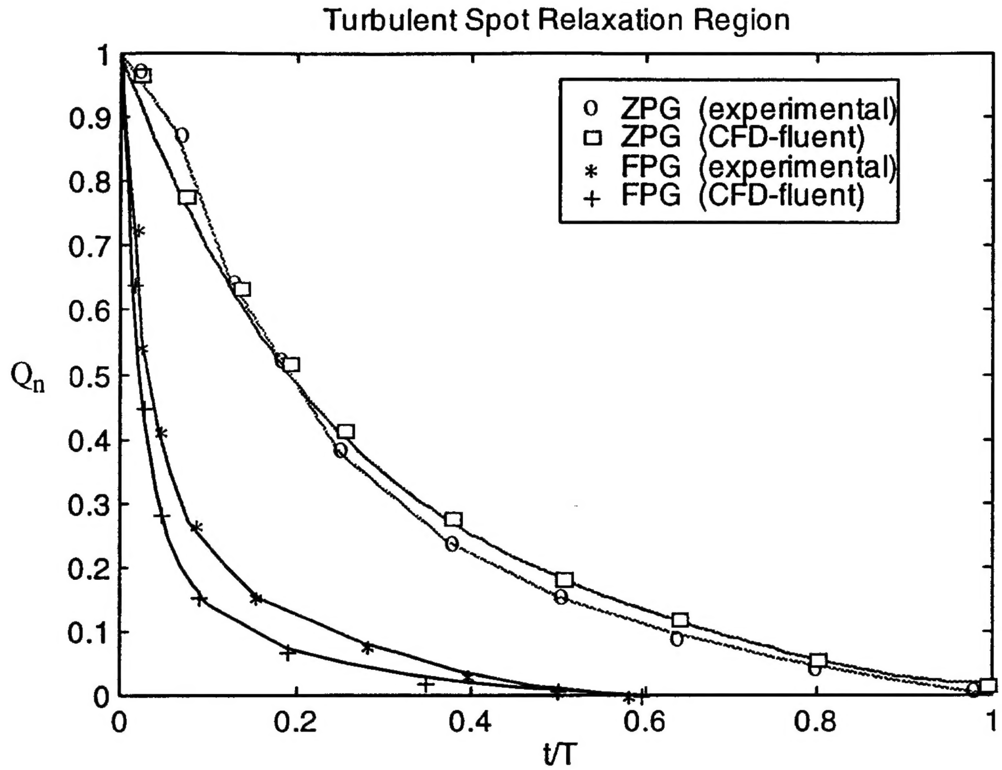



**Figure 10.** Relaxation of surface heat transfer in the becalmed region: CFD & Experimental. The heat transfer rate falls as the laminar boundary layer returns to the steady state profile. A favorable pressure gradient (FPG), results in the acceleration of a flow which stabilizes the boundary layer, thus effecting the rate at which heat transfer decays. A zero pressure gradient flow (ZPG), is represented by a constant freestream Mach number flow and is inherently less sta-

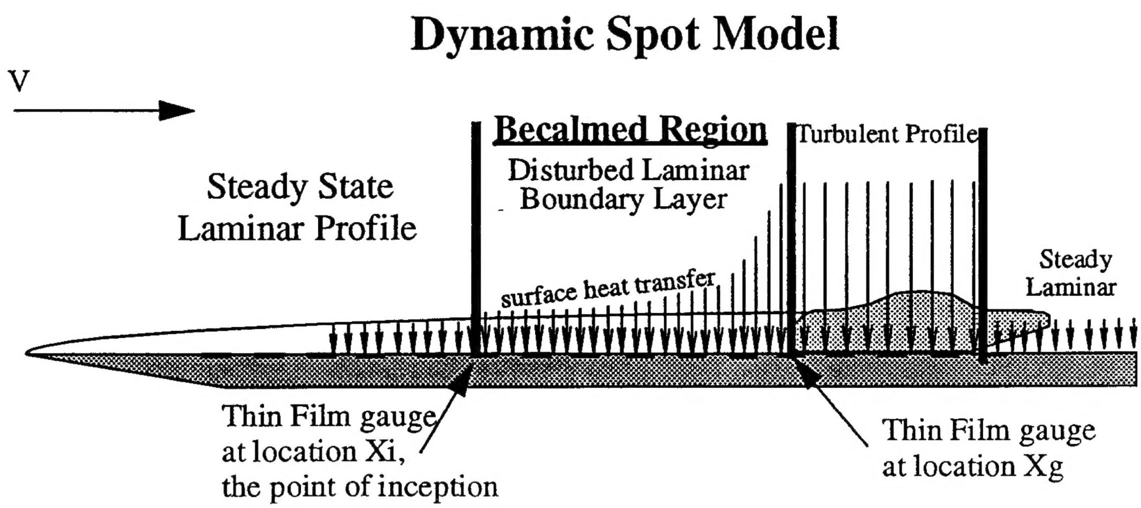



**Figure 11.** the becalmed region accounts for a significant portion of heat transfer resulting from the passing of a turbulent spot. This region has been neglected in the past but can now be

# The Dynamic Spot Model Software

Inputs: spreading angle, leading and trailing edge velocities, generation rate, and location of transition onset.

Output: Intermittency and spot trajectories.

## Surface heat transfer from four locations on the plate.

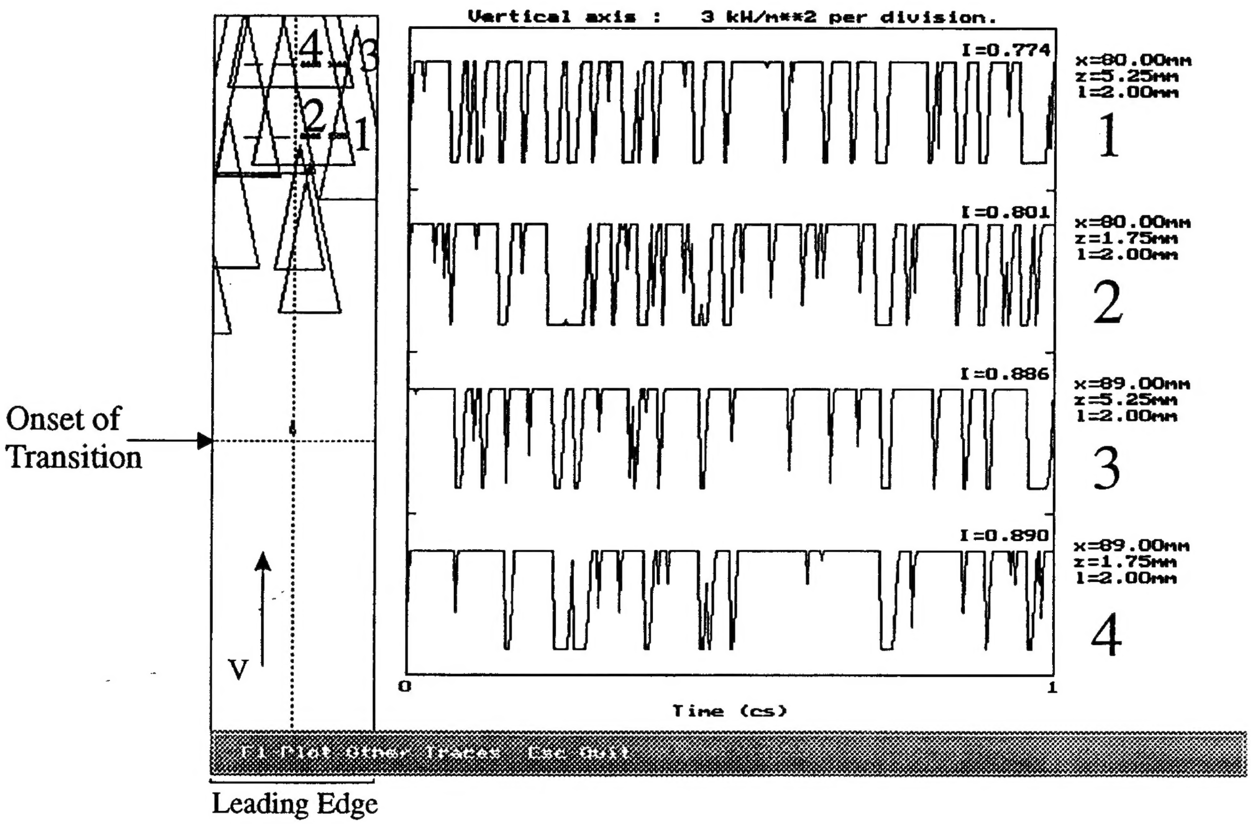



**Figure 12.**

## Dynamic Spot Model Simulation

The numerical routine which has been used to predict the trajectories and heat transfer levels of the entire turbulent spot transition zone is best demonstrated by the flow chart in figure 13.

One subroutine will make an initial calculation of the intermittency for the entire transition zone (2D: x and z, t). The spot locations (which have been generated randomly), are then compared with the user's desired spanwise distribution (i.e., Gaussian, Dirac-Delta, Point-Source), which is defined by the input standard deviations in the stream-wise and spanwise directions. If the distributions are not satisfied then the subroutine is repeated and a new set of spots is generated. This process is repeated until a spot distribution which satisfies the criteria has been obtained.

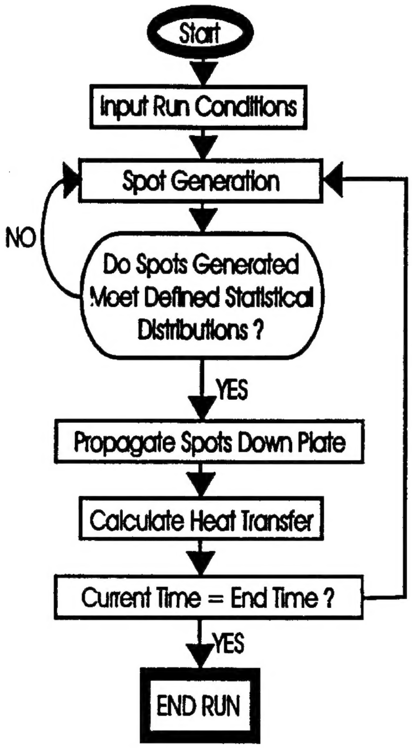



**Figure 13.**

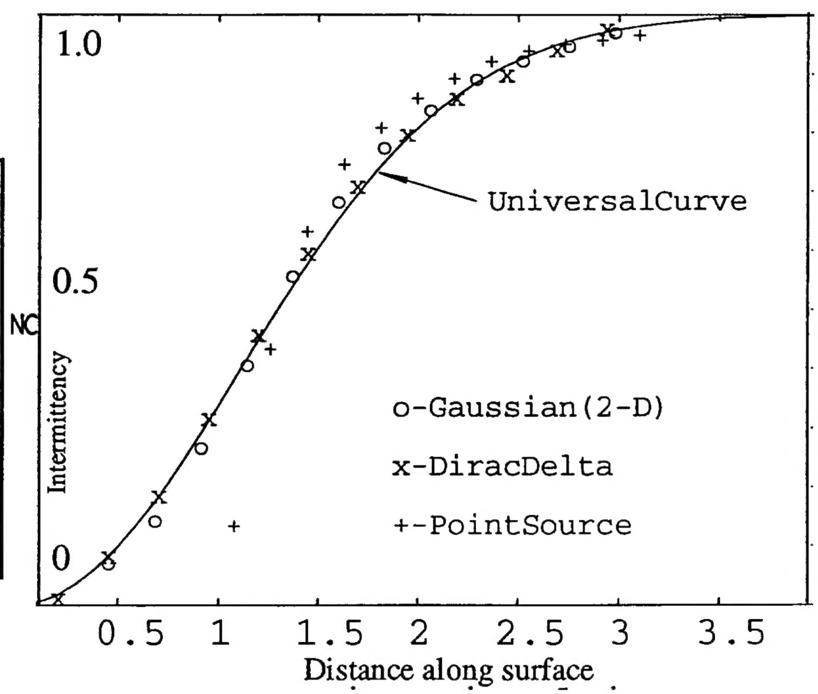



**Figure 14.** Intermittency output from the numerical model for three spanwise statistical spot distributions.

The engine of the model is calculated from the intermittency model:

$$\gamma(x) = 1 - e^{\left\{\frac{-(x-x_t)\,n\sigma}{U_\infty}\right\}}$$

where intermittency ($\gamma$), is a function of the transition location, spot generation rate, non-dimensional spot-propagation parameter, and freestream velocity. The spanwise distribution of spots is defined by a user-defined statistical model which is combined with the intermittency model to quantify all spot locations in the transition zone.

# Results

| Condition | $C_{le}$ | $C_m$ | $C_{te}$ | Spreading Angle (degrees) | Generation Rate | Tu (%) |
|---|---|---|---|---|---|---|
| M=0.17 | 0.89 | 0.53 | 0.66 | - | 6.25e-4 | 1.7 |
| M=0.20 | 0.89 | 0.54 | 0.65 | - | 5.15e-4 | 0.8 |
| M=0.24 | 0.86 | 0.56 | 0.65 | 9.9 | - | 0.2 |
| M=0.28 | 0.90 | 0.50 | 0.68 | 9.2 | - | 0.2 |
| M=0.38 (NFD) | 0.6-0.7 | 0.45 | 0.57 | - | - | 0.2 |
| M=0.38 | 0.89 | 0.49 | 0.64 | - | 6.16e-4 | 0.2 |
| M=0.55 | 0.81 | 0.56 | 0.65 | 8.2 | - | 0.2 |
| 1.32 | 0.85 | 0.54 | 0.64 | 6.0 | - | - |
| 1.86 | 0.83 | 0.53 | 0.64 | - | - | - |
| Mild Favorable | 0.92 | 0.60 | 0.53-0.77 | 3.9 | - | - |
| Strong Favorable | 0.87 | 0.63 | 0.5-0.85 | 3.3 | - | - |
| Mild Adverse | - | - | - | 13.4 | - | - |

**Figure 15.**

$NFD \equiv$ Not Fully Developed Turbulent Spot

$C_{le} \equiv$ Leading Edge Fractional Propagation Velocity

$C_m \equiv$ Mean Fractional Propagation Velocity

$C_{te} \equiv$ Trailing Edge Fractional Propagation Velocity

$N_o \equiv$ Non-Dimensional Turbulent Spot Generation Rate